Modeling Water Uptake of Dust in the Indoor Environment

Undergraduate Research Distinction in Environmental Engineering Thesis

By

David Kormos

Environmental Engineering

The Ohio State University

2019

Thesis Committee

Karen Dannemiller, Advisor

Andrew May

Abstract

Moisture found within homes can impact microbial growth in dust and contribute to negative human health effects. There are mathematical models of the adsorption of moisture on outdoor particles, but there is currently no mathematical model for moisture uptake and microbial growth in dust within homes. The goal of this research was to use an atmospheric mathematical model to inform a model for indoor dust to predict moisture uptake. Thermodynamic and kinetic models were utilized with Arizona Test Dust, a well characterized model dust. To compare to the thermodynamic models, the dust was incubated at equilibrium relative humidity conditions from 50-100% in intervals of 10% for 1-day increments. Two thermodynamic models were evaluated, one using values obtained from literature (Model A), and the other using values based on our experimental data (Model B). To compare to the kinetic model, we increased the relative humidity from 50% to 100%, and tested at time points up to 6 hours. Two kinetic models were used, one modeled as spherical particles and the other based on a planar sample. Water activity and water content were used to infer water intake. Mass ratios and differences were measured to compare to the previous atmospheric models. The thermodynamic experiments resulted in an exponential curve, similar to the model, however the mass ratio in the model was approximately 70% higher than the results at 100% ERH, 20% higher at 90% ERH, and 5% higher at 80% ERH for Model A. This demonstrates that the

dust is absorbing less water than predicted by the model. For Model B, all the samples were within 5% error at all ERH values, except for 100% ERH. The kinetic experiments resulted in the model and the observed data closely matching at 82% ERH when accounting for a planar model, but at 100% and 95% ERH, the equilibrium mass difference was double the model prediction. This could be due to condensation in the cup. A hysteresis effect was observed, showing that the dust retained water after reaching the 100% ERH value. The growth of microbial species caused a decreased hysteresis effect. Future work will consist of further testing of the models with both the model dust and house dust with the ultimate goal of improved modeling of water uptake in indoor dust.

Acknowledgments

I would like to thank my advisors, Dr. Karen Dannemiller and Dr. Andrew May, for providing support and guidance throughout the entire project. I would also like to thank the members of my lab group, Ashleigh, Sarah, Sam, Iona, Nick and Victor, for helping me with different aspects of my project. I'm also very thankful to Dr. Gil Bohrer for providing some guidance on some of the aspects of the project as well. I want to also thank my family, for providing me with endless support in pursuing my goals, and always giving me encouragement and love.

Thank you to the College of Engineering Undergraduate Research Office for awarding me the Undergraduate Research Scholarship, and the Undergraduate Research Office for funding my trip to Brazil to present my research. Thank you to the Big Ten Alliance for my acceptance in the Student Research Opportunities Program, which provided me with funding during the summer to conduct my research. Lastly, thank you to the Alfred P. Sloan Foundation, which provided some of the funding to collect the dust used in this project.

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

We spend 90% of our time indoors [1] where we are exposed to a diverse community of fungi and bacteria as well as chemical mixtures that can impact our health. These microorganisms and chemicals are present in dust, which is an important source of human exposure that can be resuspended from surfaces due to human activity [2]-[6]. Previous studies have indicated a correlation between moisture damage and mold within main living quarters and the risk of developing asthma in early childhood [7]. Although this correlation between moisture and asthma has been observed, these effects are not directly due to the water, and the mechanisms remain unclear [8]. The estimated cost of illness for asthma caused by dampness and mold in the United States is approximately $15.1 billion for asthma morbidity, and $1.7 billion for asthma mortality [9].

Understanding how relative humidity and water availability affect water uptake, and therefore microbial growth in dust, is important for creating a more extensive characterization of the indoor environment. Parts of the population with asthma will benefit from this research, since rather than mitigating the problem through medication, we can focus on the environmental exposures, which will have a more direct effect. The new framework that will result from this study of how to predict microbial growth in indoor dust may be used to inform models in microbiology, ventilation, public health, and policy. The availability of water is the limiting factor for microbial growth in the indoor environment. Microbial growth in dust indoors can be attributed to the amount of water the dust can uptake. The moisture in dust may be measured as water activity, which measures water availability and has previously been used in the food industry [10]. Therefore, water activity is more useful in describing microbial content rather than water content [10]. Water activity is related to the equilibrium RH (ERH), which is the RH of a product when exposed to the environmental RH [10]. We will refer to ERH for our dust and atmospheric interactions.

Microbial growth may occur under elevated relative humidity conditions that can happen indoors and may contribute to half of human microbial exposure [11]. The “time-of-wetness” concept states that the amount of microbial growth depends upon the time spent above a moisture availability threshold [12], and currently a mathematical model is being developed specifically for dust based on this model. However, there is no mathematical description of water uptake by indoor dust.

Different models have been developed in the past for interactions between water and atmospheric particles. The chemical composition of airborne particles affects gas-liquid equilibrium for the moisture, and therefore affects the mass of the particles [13]. Understanding the amount of water in airborne particles has important implications for cloud formation, visibility degradation, and aqueous chemistry [14]. Water uptake for airborne particles may occur as absorption or adsorption and the sorption is dependent on the phase of the particles. Liquid particles gradually absorb water while solid particles absorb water spontaneously and become an aqueous solution at a deliquescence RH with increasing RH [13]. In desorption, with decreasing RH, hysteresis occurs, showing that the particle will retain some liquid after reaching the deliquescence RH [13]. According to literature, hysteresis may be altered from different compounds and the presence of organic compounds [15], [16].

The atmospheric models include a thermodynamic model, which accounts for the relative humidity, and uses hygroscopicity (κ) to represent the water activity as proposed by Petters and Kreidenweis [14]. The thermodynamic model can describe the equilibrium amount of water contained in the dust at a particular relative humidity level. Higher κ values point towards hydrophilic substances, and lower values are associated with hydrophobic substances. Hydrophilic substances interact well with and can absorb water, while hydrophobic substances do not exhibit the same behaviors. Dust mites and quartz particles are hydrophilic, while cat fur and dog fur, and some human skin cells are hydrophobic. Dust resuspension is heavily influenced by a particles ability to absorb water as well. It has been found that increasing RH can decrease resuspension for hydrophilic substances to form film adhesion layers [17]. Particle diameter is also important, as supermicron particles like mineral dust [18]-[20] have low κ values but take up relatively large amounts of water due to their size. Sometimes water uptake may be kinetically limited [21, 22], and thus the time rate of change of a particle's diameter must be considered. Kinetic models are able to predict the time required to absorb a certain amount water. However, the existing models based on atmospheric particles have not yet been extended to indoor dust.

The main goal of this work is to develop a mathematical model to represent water uptake by indoor dust. Indoor dust particles generally have a similar composition to atmospheric particles, containing chemical species like minerals [23, 24], trace metals [23]-[25], and organic compounds [25]-[29], and biological components [30]-[37]. However, the specific chemicals within the dust may be vastly different than in the atmosphere though, as well as the biological components, including human skin cells, dust mites, and animal dander. However, due to the high-level similarities, we still expect the dust to still behave relatively similar with regards to water uptake.

Chapter 2. Materials and Methods

Chamber experiments were utilized to test both thermodynamic and kinetic models of moisture uptake in indoor dust. For these chamber experiments, a well-characterized model dust was used to determine which model best represented the water uptake of the dust. For the thermodynamic model experiments we allowed the dust to reach equilibrium and measured the masses at the equilibrium points. The kinetic experiments included measuring the mass of the dust as it was exposed to heightened RH conditions until it reached the equilibrium point.

Arizona Test Dust

The model dust, called Arizona Test Dust, has been well characterized. The size distributions for the four classes of dust are provided in Figure 1, and was certified by the vendor (Powder Technology, Inc., Arden Hills, MN). Based on previous work, class A4 is the most representative of indoor dust due to the size distributions being coarser [24], while A2 is a finer dust. A2 and A4 class dusts were received from the vendor, to allow for comparison between coarser and finer dusts in the experiments. Arizona Test Dust is comprised mainly of silica (69-77% by weight) and aluminum oxide (8-14%). The inferred κ value, which Koehler et al. [18] interpreted from results from Vlasenko et al.

[39], is 0.025. The density of the dust, as provided by the vendor, is 2.65 g cm-3. This allows for Arizona Test Dust to be utilized to select the appropriate model (thermodynamic or kinetic) for the water uptake by indoor dust compared as RH changes.

Chambers

Chamber experiments consistent with previous protocols were conducted with the model dust [11], where samples of dust were incubated at 25 °C in 3.8 L jars with relative humidity being controlled in each chamber. The RH in the chamber is an equilibrium RH (ERH) as it is in contact with the dust. The cups that the model dust samples were placed in was covered in tinfoil that was baked at 550 °C and any containers were autoclaved to provide a sterile environment. The top of each glass jar was covered with parafilm. The ERH control chamber the dust was incubated in can be seen in Figure 1, and the Arizona Test Dust is shown in Figure 2.

Figure 1: ERH control chamber setup. Inside of the chamber is the salt solution and the HOBO logger, and it is covered with Parafilm.

Figure 2: Arizona Test Dust in the sampling cup. This cup is used with the water activity meter to test the water activity. Baked aluminum foil is placed in the cup or sterility.

Salt solutions were made to control RH conditions inside of the chambers and utilized $MgCl_2$ and NaCl. For 50, 60, and 70% ERH, 42.84, 37.76, and 30.76 grams of MgCl2 was added to 100 mL of DI water respectively. For 80, 85, 90, and 95% ERH, a total of 30.21, 23.37, 17.21, and 13.11 grams of NaCl was added to 100 mL of DI, respectively. For 100% ERH 100 mL of deionized water was used. 100 mL of the salt solutions were placed inside of the chambers to simulate the different ERH conditions. The water activity of each salt solution and dust sample was measured on an Aqualab 4TE Dew Point Water Activity Meter (Decagon Devices, Pullman, WA, USA). Salt solutions were adjusted if needed after measurement of water activity. Onset HOBO loggers (Bourne, MA USA) were placed in the chambers to measure RH during the experiments.

Thermodynamic Experiments

First, we wanted to evaluate the validity of the thermodynamic model. The dust was incubated at ERH from 50-100% in intervals of 10% for 1-day increments. Setting the sample to sit in the chamber for 1 day allowed it to reach an equilibrium point where the condensation and evaporation rates are equal, so there would be no additional net uptake. After each equilibrium point was reached, the mass and the water activity were measured, and then the sample was placed into the next chamber. Mass ratios, using 50% ERH as the base value, were calculated to compare to the atmospheric models. This mass ratio was used in order to ensure that every mass value at the succeeding ERH levels was normalized using the mass obtained at 50% ERH. 50% ERH was chosen because it represented a recommended indoor RH level by the EPA [40]. After reaching 100% ERH, we placed the dust in the lower ERH conditions until it reached 50% again, to observe the hysteresis effect. Each sample was run in triplicate, with three samples in a jar. Two trials were run simultaneously. The timeline for the thermodynamic experiment for the A2 and A4 dust trials is shown in Table 1.

Table 1: Thermodynamic sampling timeline. This timeline shows the process for sampling 2 samples in triplicate, including when the dust was placed in the chamber and when it was taken out and tested.

Jar	Day													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
50%	Set Up	A2	Test A2/ A4	Test A4/ Parafilm	X	X	X	X	X	X	Set Up	A2	Test A2/ A4	Test A4/ Parafilm
60%	X	Set Up	A2	Test A2/ A4	Test A4/ Parafilm	X	X	X	X	Set Up	A2	Test A2/ A4	Test A4/ Parafilm	X
70%	X	X	Set Up	A2	Test A2/ A4	Test A4/ Parafilm	X	X	Set Up	A2	Test A2/ A4	Test A4/ Parafilm	X	X
80%	X	X	X	Set Up	A2	Test A2/ A4	Test A4/ Parafilm	Set Up	A2	Test A2/ A4	Test A4/ Parafilm	X	X	X
90%	X	X	X	X	Set Up	A2	Test A2/ A4	Test A4/ A2	Test A2/ A4	Test A4/ Parafilm	X	X	X	X
100%	X	X	X	X	X	Set Up	A2	Test A2/ A4	Test A4/ Parafilm	X	X	X	X	X

We analyzed the two different types of dust (A4 and A2) to determine if particle size of the dust would affect the results. Similarly, different mass amounts of the A4 and A2 dust were analyzed, to determine if the mass in the cup affected the water uptake. A4 dust is a coarser dust and is supposed to simulate indoor dust more precisely than the finer A2 dust. Equation 1 below was used for creating the model for predicting the mass ratio at different relative humidity levels. κ, refers to the hygroscopicity, which according to literature is approximately 0.025 for Arizona Test Dust [18]. This value is for resuspended dust in the atmosphere, and the Solver function in Excel was used to find a better fitting value between the trials based on our experimental data. The κ was then multiplied by the ratio of the density of water (1 g cm^{-3}) and the density of the Arizona Test Dust (2.65 g cm^{-3}). The equation solves for the predicted mass ratio of dust at a specific ERH as compared to dried out dust. To normalize the model for 50% ERH as the base, each prediction was divided by the value predicted at 50% ERH.

$$\frac{m}{m_0} = \frac{\kappa \rho_w}{\rho_p} / (\frac{1}{RH} - 1) \quad (1)$$

Kinetic Experiments

As with the thermodynamic model, we also wanted to evaluate the validity of the kinetic model. We began with a resting value of 50% ERH, moved the dust to a higher ERH, and tested different time points until the equilibrium point was reached. Equilibrium points were reached at approximately 3-4 hours, and time points were taken about every 5 minutes for the first hour, and every 30 minutes to one hour thereafter. At each of these time points, the parafilm would be removed, and we would quickly take water activity and mass values of the sample before placing it back in the relative humidity chamber. These samples were also run in triplicate, however not simultaneously, due to the time sensitivity. Also, for these experiments we only used A4 dust to more closely model indoor dust. A homogeneous mixture was assumed for the model dust, so multiple replicates of a sample could be utilized in the analysis for a model comparison, due to the nature of the chamber, and how much time the sample would spend exposed to ambient air for sampling. The experiment was run for 82%, 95%, and 100% ERH. Equation 2 below describes mass transfer to a spherical particle. For A4 dust, $d_{p,dry}$ (the approximate mass mean diameter) is 40 μm, and the number of particles (N) is approximately 2 x 10^7 particles. We also added a scaling factor of 4 x 10^{-6} to this equation because not all the dust is in contact with the air, which will affect the mass transfer.

$$m_w(t) = \rho_w \frac{\pi}{6}\left(d_{p,wet}^3(t) - d_{p,dry}^3\right)N \quad (2)$$

Equation 3 below describes mass transfer to a planar surface. In the equation, m_w is the mass of water adsorbed to the dust, m_{dust} is the mass of dust, k_m is the mass transfer coefficient, A is the surface area of the dust, ρ_{dust} is the density of the dust, ρ_w is the density of water, $p_{vap}(T)$ is the saturation vapor pressure of water at temperature T, M_w is the molar mass of water, R is the ideal gas constant, T is the temperature, and S is the saturation ratio of water vapor in air. The κ value used for the kinetic model equation was 0.025.

$$\frac{dm_w}{dt} = k_m A \frac{p_{vap}(T) M_w}{RT}\left(S - \frac{\frac{m_w(t)}{m_{dust}}}{\kappa \frac{\rho_w}{\rho_{dust}} - \frac{m_w(t)}{m_{dust}}}\right) \quad (3)$$

Microbial Growth Preliminary Trials

One of the future goals of this project is to create a model to determine how water uptake effects microbial growth in the dust, and conversely, how microbial growth might affect the water uptake and how the microbes and moisture interact. Indoor dust samples were collected from vacuum bags from 2 different homes and sieved to produce a finer dust. These samples were then put through chamber experiments using the thermodynamic setup to create a baseline for comparison, and then placed into a 100% ERH chamber for 2 weeks. These 2 weeks allowed for microbes and fungi to grow on the dust when exposed to the extreme ERH conditions. After, the thermodynamic set up was performed once again on the samples. The trials were then compared to see how the moisture and microbes interacted.

Chapter 3. Results

Thermodynamic Experiments

The thermodynamic experiments resulted in an exponential curve, which is the same shape as the model. Each trial of dusts sampled can be seen in Figures 3 and 4 below, with the ERH on the x-axis, and the mass ratio on the y-axis. This mass ratio was created utilizing the mass at 50% ERH as the base value. The water activity of the dust ranged from being 4% higher than the ERH in the chamber at 50%, to 10% lower at 100% ERH. Variability between replicates was low from 0.03%-1% coefficient of variation. The water activity readings were more inconsistent for the samples with 0.5 g of material compared those with 2 g. When comparing the experimental values to the original model, represented by Model A (Figures 3 and 4), the κ value was set at 0.025 to match literature. This value, as noted earlier, describes the resuspended dust rather than the dust on the ground, so this value could be different. A second model was used by creating a best fit line for all the sample trials. The calculated value for κ was 0.003425, represented by Model B. For Model A, the mass ratio in the model was approximately 70% higher than the results at 100% ERH, 20% higher at 90% ERH, and 5% higher at 80% ERH. This shows that the dust was not taking up as much water as expected. For Model B, the error margin was within 5% for all relative humidity values below 95%. 100% ERH was undefined due to the equation for the model.

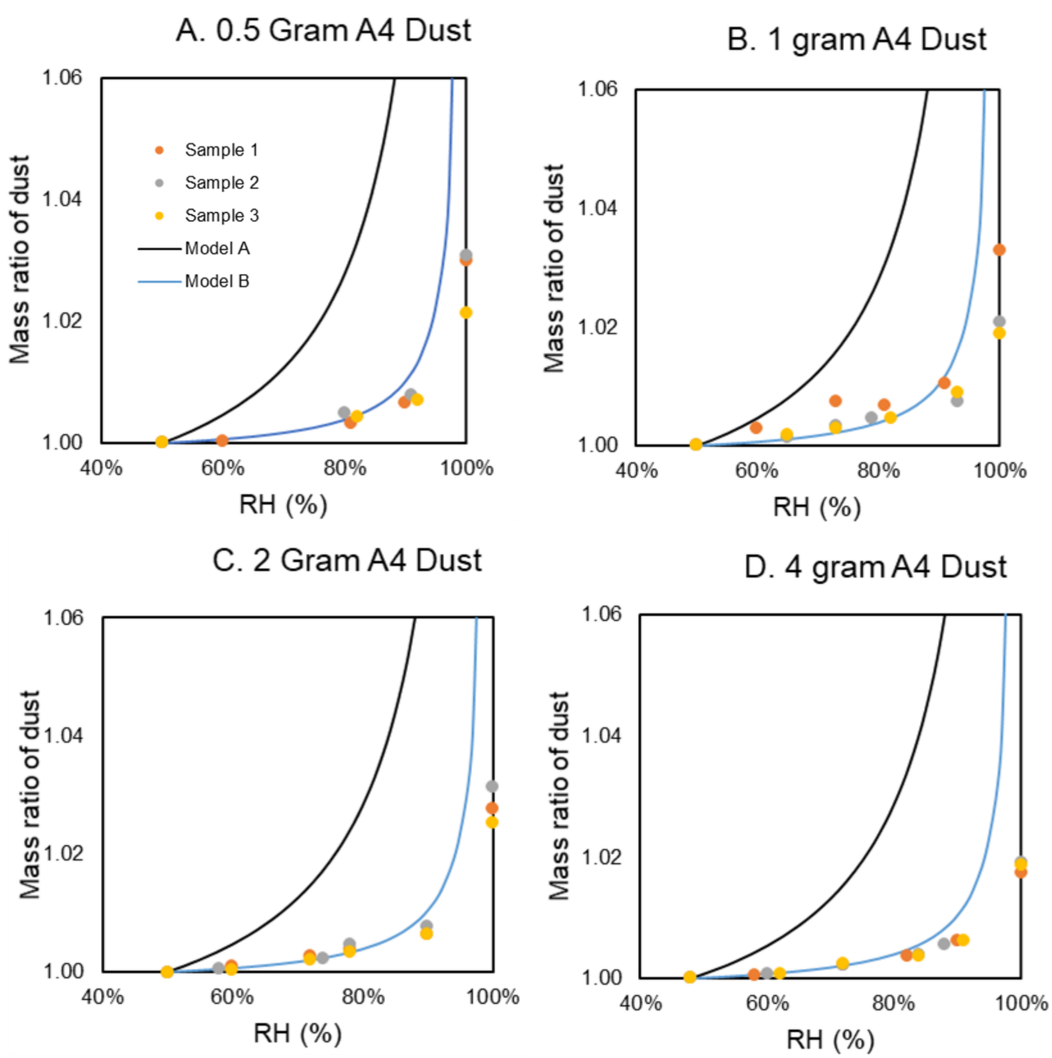

Figure 3: Thermodynamic Model Comparisons with Arizona Test Dust, A4 Dust. The sample experiments are plotted on the same axes as two models calculated with different kappa values. The y-axis represents the mass ratios of the dust, and the x-axis is the relative humidity. (A) 0.5 g of A4 dust in the cup. (B) 1 g of A4 dust in the cup. (C) 2 g of A4 dust in the cup. (D) 4 g of A4 dust in the cup.

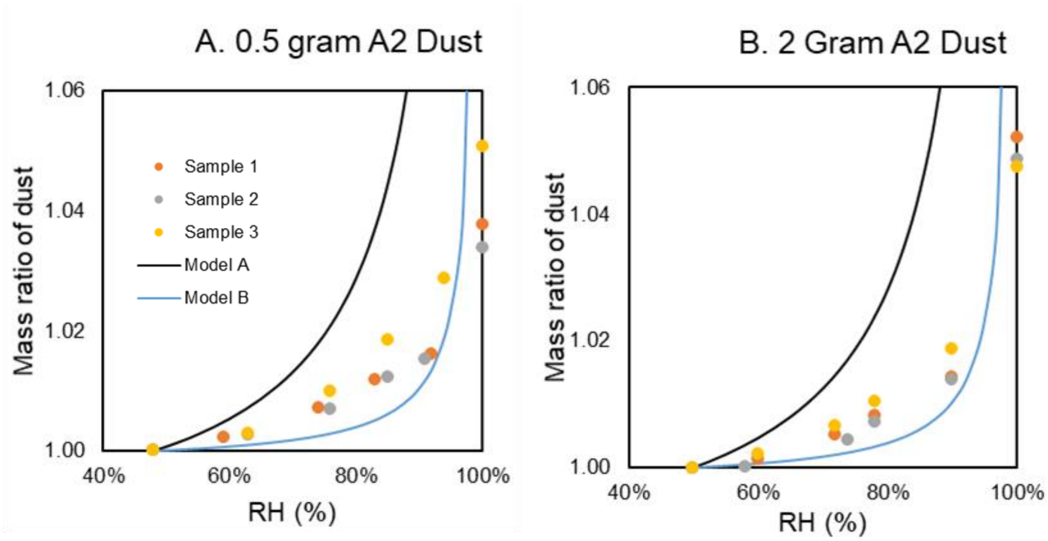

Figure 4: Thermodynamic Model Comparisons with Arizona Test Dust, A2 Dust. (A) 0.5 g of A2 dust in the cup. (B) 2 g of A2 dust in the cup.

Most of the samples observed displayed some hysteresis (Figures 5 and 6). The 0.5 g A4 sample did not demonstrate hysteresis (Figure 5). Hysteresis was observed starting around 90% ERH for the Arizona Test Dust, as evidenced by many of the samples having the same mass ratio with increasing RH and decreasing RH at 90% ERH.

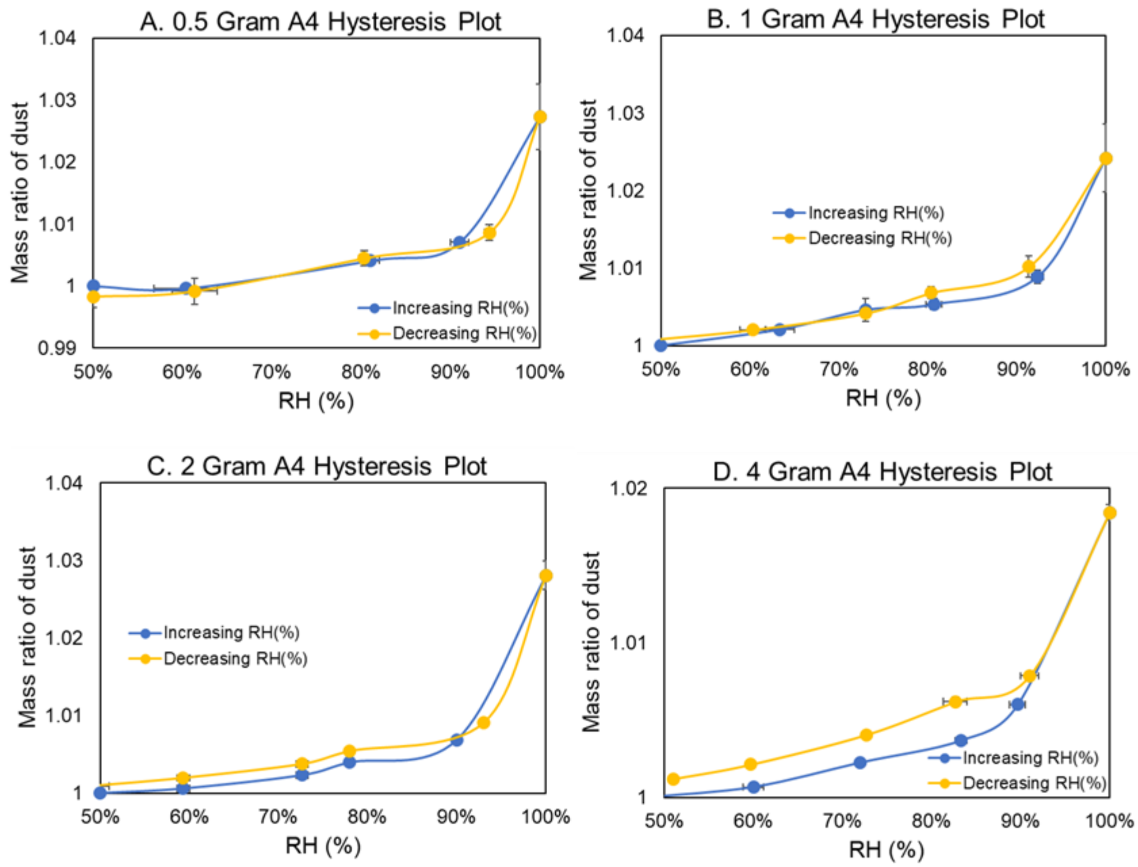

Figure 5: Hysteresis plots for the thermodynamic experiments for A4 dust. The mass ratio values when exposed to increasing RH are plotted with the mass ratio values from decreasing RH to determine if hysteresis occurs, and at what RH. Same axes as the thermodynamic model comparisons. (A) 0.5 g of A4 dust in the cup. (B) 1 g of A4 dust in the cup. (C) 2 g of A4 dust in the cup. (D) 4 g of A4 dust in the cup.

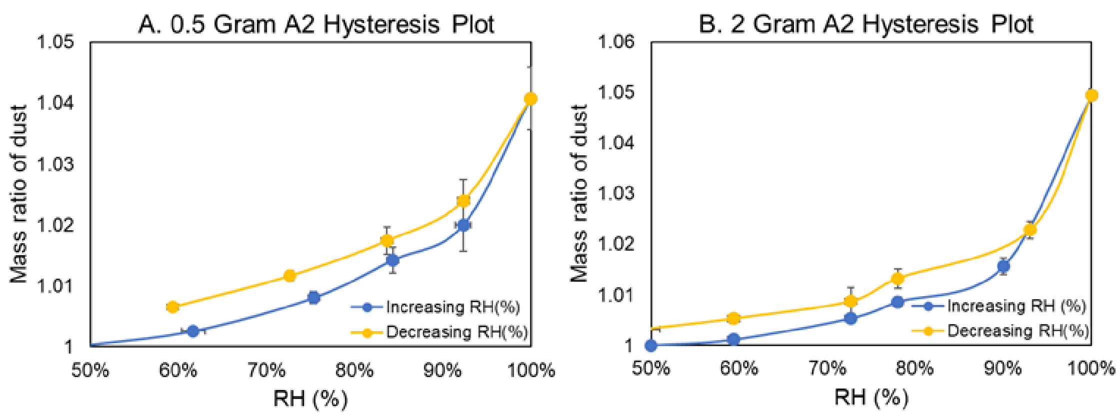

Figure 6: Hysteresis plots for the thermodynamic experiments for A2 dust. (A) 0.5 g of A2 dust in the cup. (B) 2 g of A2 dust in the cup.

Kinetic Experiments

The planar model and the experimental data closely matched in the kinetic experiments conducted at 82% ERH (Figure 7). In the figures, the x-axis represents the elapsed time from the start of the experiment, and the y-axis represents the mass of water within the sample. This value was determined by calculating the difference between the mass of the sample at the elapsed time and the mass of the sample at the base value of 50% ERH at the initial time point. The mass difference data matched both the spherical and planar model closely for the first hour at 82%, 95%, and 100% ERH. At 95% ERH (Figure 6) the experimental data had an equilibrium point above the planar model, and below the spherical model. For the 100% RH experiments, in Figure 6, the data overpredicted for the planar model throughout the modelling time. For the 100 % ERH experiments, the equilibrium mass difference was double the model prediction.

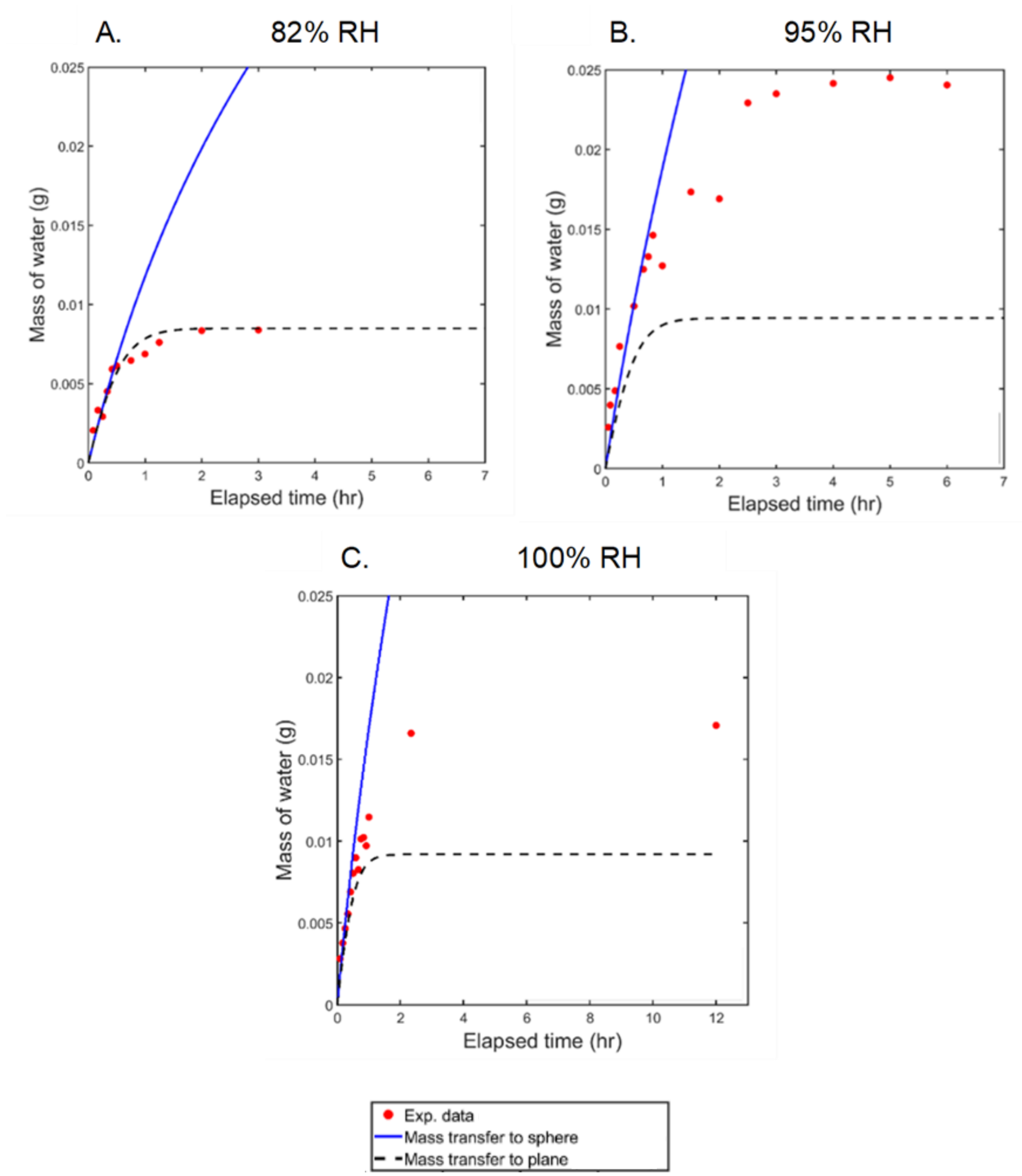

Figure 7: Kinetic Model Comparisons with 2 g of A4 dust. The sample experiments are plotted on the same axes as two models calculated with different surface areas. The y-axis represents the mass gain of the dust, and the x-axis is the elapsed time. (A) 82% ERH trials with A4 dust. (B) 95% ERH trials with A4 dust. (C) 100% ERH trials with A4 dust.

Microbial Growth Preliminary Trials

The results of the microbial growth experiments demonstrated a hysteresis effect with the indoor dust without microbial growth (Figure 8). There was separation between the ascending and descending lines. The hysteresis effect is also present in atmospheric particle models. Thus, after the dust reached equilibrium at 100% ERH, there was residual water content that stayed within the dust even after it reached equilibrium at the lower relative humidity values. We also saw substantial variability between Site A and Site B, indicating the possibility that different microbial content can affect the water uptake of dust samples. Fungal growth present on the dust also affected the water absorption.

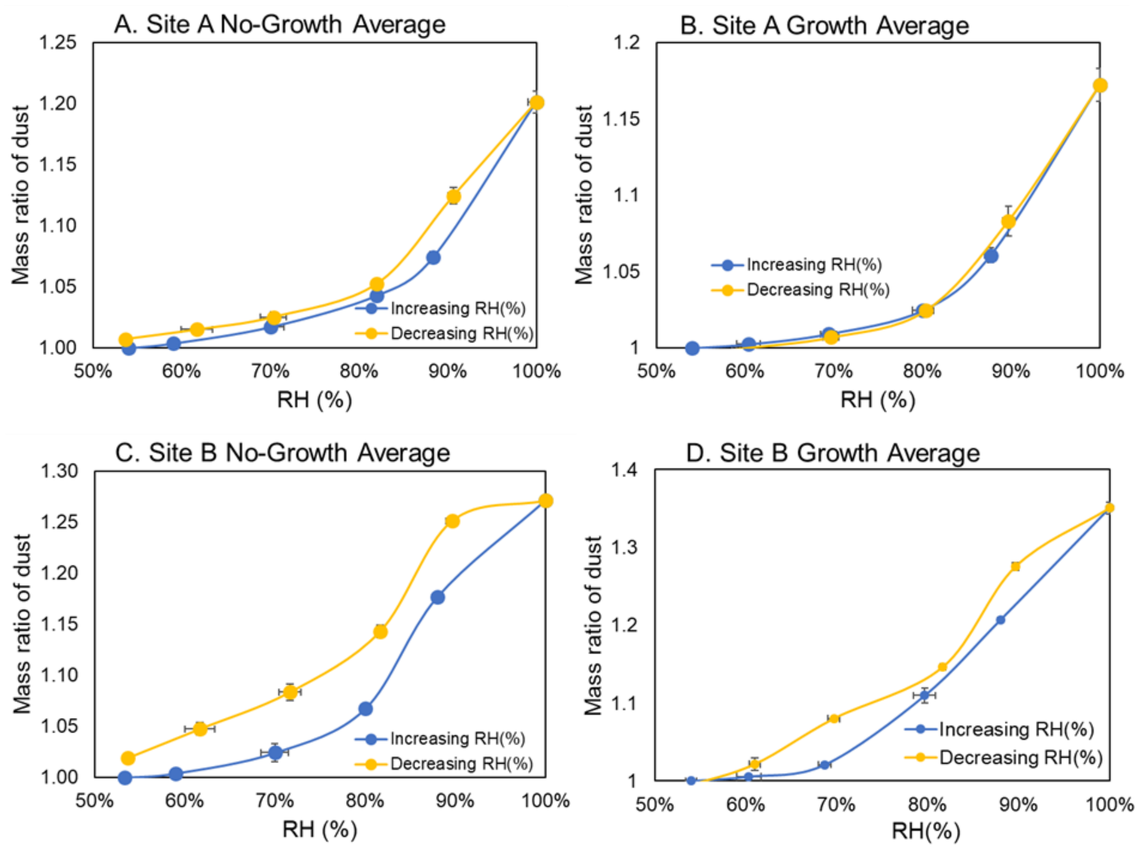

Figure 8: Thermodynamic hysteresis plots using indoor dust. The plots before allowing for fungal growth are on the left, and the plots after letting fungal growth occur are on the right. (A) First site hysteresis plot before microbial/fungal growth. (B) First site hysteresis plot after microbial/fungal growth. (C) Second site hysteresis plot before microbial/fungal growth. (D) Second site hysteresis plot after microbial/fungal growth.

Chapter 4. Discussion

Under elevated RH conditions, there were observable trends for both the thermodynamic and kinetic chamber experiments similar to those exhibited by atmospheric particles. The chemical and biological composition of dust and atmospheric particles are similar at a high level [23-37] but have some specific chemical differences and biological components like human skin cells, dust mites, and animal dander. The Arizona Test Dust we used for our experiments are finer than actual indoor dust, and do not have the same levels of biological and chemical components. The A4 class of dust matches closely for modelling purposes.

Thermodynamic Experiments

The experimental data observed from the chamber experiments utilizing the thermodynamic equilibrium approach resulted in an exponential growth of the mass ratio as ERH increased. This is consistent with the exponential trend of the atmospheric models, but the model made from the given κ overpredicted the mass ratio growth. The model that used the calculated κ value from the Solver function in Excel matched the experimental data very well. This could indicate the need for a correction factor in the model, caused by the different composition and orientation of the dust in the cup. Dust within the cup has a higher surface area and more depth than an atmospheric particle, so the need for some correction to the model is expected. The A4 dust was more consistent with the model than the A2 dust, which is consistent with the A4 class being like indoor dust. Additionally, the A2 dust has a surface-to-volume ratio due to the finer particle size, therefore it more readily absorbs the water from the atmosphere. The mass of the dust in the cup was also an important factor, since at lower mass values (under 2 grams), the measurements were more inconsistent, and we were unable to take accurate water activity readings. The results from these experiments provide a good basis for the development of a model that could predict the water uptake of indoor dust.

The hysteresis graphs formed from the data were consistent with literature describing this effect, with 4 of the dust trials showing this effect, and 2 of them not [13]. The two that did not display hysteresis were the lower mass samples, so there could have been some measurement error. More trials need to be conducted with the model dust and indoor dust must be analyzed before any definitive claims can be made.

Kinetic Experiments

The experimental data observed from the chamber experiments utilizing the kinetic time-step approach resulted in a rapid growth of the mass difference with time until it reached its equilibrium. This was consistent for the three ERH values tested. The consistency with the models was varied for the different ERH conditions. For 82% ERH, the data matched both models for the first hour, then reached the same equilibrium as the planar model. For 95% ERH, the data matched both models for the first 30 minutes, then continued past the theoretical maximum water uptake for the planar model and matched the spherical model for the first hour. The dust then reached its equilibrium point at approximately 0.017 grams, about 0.007 grams higher than the theoretical. The results for 100% ERH were similar to the 95% results, except the dust reached a higher equilibrium point of approximately 0.024 grams, more than double the theoretical limit. This could be due to condensation onto the foil cup with the high ERH conditions. Kinetic experiments for other ERH values between 80% and 95% ERH should be conducted to determine if there is an observable spontaneous increase in mass difference, possibly linked to the deliquescence RH.

Microbial Growth Preliminary Trials

The hysteresis effect observed in the results from the indoor dust before allowing for microbial and fungal growth were consistent with previous literature and showed that the dust had reached its deliquescence RH [13]. After reaching this deliquescence RH, the dust retained moisture while going through desorption, possibly due to becoming an aqueous solution after exposure to the high RH conditions. After allowing for the fungal and microbial growth in the dust, both indoor samples exhibited less of a hysteresis effect in desorption, which is consistent with literature stating that different microbes and organic compounds can influence deliquescence and hysteresis [13], [14]. These results show that the microbial and fungal growth affect how dust and moisture interact and could potentially affect the water uptake.

Limitations

The main limitations present within this project pertained to human error within the experiments, spacing for the number of chambers needed, timing, and the difficulty of the chamber experiment set up. The kinetic experiments required quick sample measurements, so the sample would not be exposed to the air for too long while outside of the relative humidity chamber. To limit this error, we could create a larger relative humidity chamber, big enough to fit all the instrumentation required for the experiments. There was also the possibility of losses of dust when transferring the cups from the chamber to the water activity meter, and then to the mass balance. The models also have limitations, since they are for the atmospheric particles, rather than dust particles. Although they have similar compositions at a high level, there is still some possibility of certain biological and chemical components being more prevalent in dust, possibly affecting the accuracy of the models. Also, the way the dust is stacked within the cup for the experiments could affect the water absorption, thus further influencing the results. To further test the validity and adjust the models, more trials with the model dust should be conducted, and then indoor dust trials.

Chapter 5. Conclusion

Arizona Test Dust growth when exposed to elevated relative humidity conditions have a similar trend to the models exhibited by models for atmospheric particle growth. We also observed the hysteresis effect in dust for both Arizona Test Dust and indoor dust samples with decreasing relative humidity conditions. Understanding these growth trends and creating models for them will help with further characterization of the indoor environment and could lead to the creation of models to help in the prediction of microbial and fungal growth when exposed to moisture. This study provides a preliminary analysis into the creation of these models to be utilized for future studies. Future work can expand upon this study by conducting more chamber experiments with the Arizona Test Dust at different ERH levels and comparing them to completely dry dust conditions, then comparing to the atmospheric models, and creating a model that can accurately predict the trends in the Arizona Test Dust. Future work should also include the further collection and testing of indoor dust samples to see how the models predict their growth.

Bibliography

[1] N. E. Klepeis, W. C. Nelson, W. R. Ott, J. P. Robinson, A. M. Tsang, P. Switzer, J. V Behar, S. C. Hern, and W. H. Engelmann, “The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants,” *J. Expo. Anal. Environ. Epidemiol.*, vol. 11, no. 3, pp. 231–252, 2001.

[2] T. Thatcher and D. Layton, “Deposition, resuspension, and penetration of particles within a residence,” *Atmos. Environ.*, vol. 29, no. 13, pp. 1487–1497, Jul. 1995.

[3] A. R. Ferro, R. J. Kopperud, and L. M. Hildemann, “Source Strengths for Indoor Human Activities that Resuspend Particulate Matter,” *Environ. Sci. Technol.*, vol. 38, no. 6, pp. 1759–1764, Mar. 2004.

[4] J. Qian, D. Hospodsky, N. Yamamoto, W. W. Nazaroff, and J. Peccia, “Size-resolved emission rates of airborne bacteria and fungi in an occupied classroom,” *Indoor Air*, vol. 22, no. 4, pp. 339–351, 2012.

[5] B. E. Boor, J. A. Siegel, and A. Novoselac, “Wind Tunnel Study on Aerodynamic Particle Resuspension from Monolayer and Multilayer Deposits on Linoleum Flooring and Galvanized Sheet Metal,” *Aerosol Sci. Technol.*, vol. 47, no. 8, pp. 848–857, Aug. 2013.

[6] Y. Tian, K. Sul, J. Qian, S. Mondal, and A. R. Ferro, “A comparative study of walking-induced dust resuspension using a consistent test mechanism,” *Indoor Air*, vol. 24, no. 6, pp. 592–603, Dec. 2014.

[7] J. Pekkanen, A. Hyvärinen, U. Haverinen-Shaughnessy, M. Korppi, T. Putus, A. Nevalainen, “Moisture damage and childhood asthma: a population-based incident case–control study,” *European Respiratory Journal*, vol. 29, no. 3, pp. 509–515, Mar. 2007.

[8] M. J. Mendell, A. G. Mirer, K. Cheung, M. Tong, and J. Douwes, “Respiratory and Allergic Health Effects of Dampness, Mold, and Dampness-Related Agents: A Review of the Epidemiologic Evidence,” *Environ. Health Perspect.*, vol. 119, no. 6, pp. 748–756, 2011.

[9] D. Mudarri, “Valuing the Economic Costs of Allergic Rhinitis, Acute Bronchitis, and Asthma from Exposure to Indoor Dampness and Mold in the US,” *Journal of Environmental and Public Health.*, vol. 2016, no. 2386596, 12 pages, April 2016.

[10] O. C. G. Adan and R. A. Samson, “Water relations of fungi in indoor environments,” *Fundamentals of Mold Growth in Indoor Environments and Strategies for healthy living*, 2011, p. 42.

[11] K. C. Dannemiller, C. J. Weschler, and J. Peccia, “Fungal and bacterial growth in floor dust at elevated relative humidity levels,” *Indoor Air*, no. May, pp. 1–10, 2016.

[12] O. C. G. Adan and R. A. Samson, “Water relations of fungi in indoor environments,” in *Fundamentals of Mold Growth in Indoor Environments and Strategies for healthy living*, 2011, p. 42.
[13] S. T. Martin, “Phase Transitions of Aqueous Atmospheric Particles,” Chem. Rev., vol. 100, no. 9, pp. 3403–3454, Sep. 2000.
[14] M. D. Petters and S. M. Kreidenweis, “A single parameter representation of hygroscopic growth and cloud condensation nucleus activity,” *Atmos. Chem. Phys.*, vol. 7, no. 8, pp. 1961–1971, Apr. 2007.
[15] J. M. Lightstone, T. B. Onasch, D. Imre, and S. Oatis, “Deliquescence, Efflorescence, and Water Activity in Ammonium Nitrate and Mixed Ammonium Nitrate/Succinic Acid Microparticles,” J. Phys. Chem. A, vol. 104, no. 41, pp. 9337–9346, Oct. 2000.
[16] M. L. Smith, A. K. Bertram, and S. T. Martin, “Deliquescence, efflorescence, and phase miscibility of mixed particles of ammonium sulfate and isoprene-derived secondary organic material,” Atmos. Chem. Phys., vol. 12, no. 20, pp. 9613–9628, Oct. 2012.
[17] Salimifard, Parichehr, et al. "Resuspension of biological particles from indoor surfaces: Effects of humidity and air swirl." *Science of the Total Environment*, vol. 583, 2017, pp. 241-247.
[18] K. A. Koehler, S. M. Kreidenweis, P. J. DeMott, M. D. Petters, A. J. Prenni, and C. M. Carrico, “Hygroscopicity and cloud droplet activation of mineral dust aerosol,” *Geophys. Res. Lett.*, vol. 36, no. 8, p. L08805, Apr. 2009.
[19] R. C. Sullivan, M. J. K. Moore, M. D. Petters, S. M. Kreidenweis, G. C. Roberts, and K. A. Prather, “Effect of chemical mixing state on the hygroscopicity and cloud nucleation properties of calcium mineral dust particles,” *Atmos. Chem. Phys.*, vol. 9, no. 10, pp. 3303–3316, May 2009.
[20] C. D. Hatch, J. S. Wiese, C. C. Crane, K. J. Harris, H. G. Kloss, and J. Baltrusaitis, “Water Adsorption on Clay Minerals As a Function of Relative Humidity: Application of BET and Freundlich Adsorption Models,” *Langmuir*, vol. 28, no. 3, pp. 1790–1803, Jan. 2012.
[21] C. R. Ruehl, P. Y. Chuang, and A. Nenes, “How quickly do cloud droplets form on atmospheric particles?,” *Atmos. Chem. Phys.*, vol. 8, no. 4, pp. 1043–1055, Feb. 2008.
[22] T. Raatikainen, R. H. Moore, T. L. Lathem, and A. Nenes, “A coupled observation – modeling approach for studying activation kinetics from measurements of CCN activity,” *Atmos. Chem. Phys.*, vol. 12, no. 9, pp. 4227–4243, May 2012.
[23] A. Luthra, A. Ravi, S. Li, S. V. Nystrom, Z. Thompson, and J. V. Coe, “Dust Library of Plasmonically Enhanced Infrared Spectra of Individual Respirable Particles,” *Appl. Spectrosc.*, vol. 70, no. 9, pp. 1546–1554, Sep. 2016.
[24] C. Lanzerstorfer, “Variations in the composition of house dust by particle size,” *J. Environ. Sci. Heal. Part A*, pp. 1–8, Apr. 2017.
[25] K. K. Kefeni and J. O. Okonkwo, “Trace metals, anions and polybromodiphenyl ethers in settled indoor dust and their association,” *Environ. Sci. Pollut. Res.*, vol. 20, no. 7, pp. 4895–4905, Jul. 2013.

[26] F. Mercier, P. Glorennec, O. Thomas, and B. Le Bot, “Organic Contamination of Settled House Dust, A Review for Exposure Assessment Purposes,” *Environ. Sci. Technol.*, vol. 45, no. 16, pp. 6716–6727, Aug. 2011.

[27] O. Blanchard, P. Glorennec, F. Mercier, N. Bonvallot, C. Chevrier, O. Ramalho, C. Mandin, and B. Le Bot, “Semivolatile Organic Compounds in Indoor Air and Settled Dust in 30 French Dwellings,” *Environ. Sci. Technol.*, vol. 48, no. 7, pp. 3959–3969, Apr. 2014.

[28] H. Fromme, B. Hilger, E. Kopp, M. Miserok, and W. Völkel, “Polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD) and ‘Novel’ Brominated flame retardants in house dust in Germany,” *Environ. Int.*, vol. 64, pp. 61–68, Mar. 2014.

[29] S. D. Mitro, R. E. Dodson, V. Singla, G. Adamkiewicz, A. F. Elmi, M. K. Tilly, and A. R. Zota, “Consumer Product Chemicals in Indoor Dust: A Quantitative Meta-analysis of U.S. Studies,” *Environ. Sci. Technol.*, vol. 50, no. 19, pp. 10661–10672, Oct. 2016.

[30] K. C. Dannemiller, J. F. Gent, B. P. Leaderer, and J. Peccia, “Influence of housing characteristics on bacterial and fungal communities in homes of asthmatic children,” *Indoor Air*, 2015.

[31] A. S. Amend, K. A. Seifert, R. Samson, and T. D. Bruns, “Indoor fungal composition is geographically patterned and more diverse in temperate zones than in the tropics,” *Proc. Natl. Acad. Sci.*, 2010.

[32] R. I. Adams, M. Miletto, J. W. Taylor, and T. D. Bruns, “Dispersal in microbes: fungi in indoor air are dominated by outdoor air and show dispersal limitation at short distances,” *ISME J*, 2013.

[33] R. I. Adams, M. Miletto, J. W. Taylor, and T. D. Bruns, “The Diversity and Distribution of Fungi on Residential Surfaces,” *PLoS One*, vol. 8, no. 11, p. e78866, 2013.

[34] J. F. Meadow, A. E. Altrichter, S. W. Kembel, J. Kline, G. Mhuireach, M. Moriyama, D. Northcutt, T. K. O’Connor, A. M. Womack, G. Z. Brown, J. L. Green, and B. J. M. Bohannan, “Indoor airborne bacterial communities are influenced by ventilation, occupancy, and outdoor air source,” *Indoor Air*, vol. 24, no. 1, pp. 41–48, 2014.

[35] S. W. Kembel, E. Jones, J. Kline, D. Northcutt, J. Stenson, A. M. Womack, B. J. M. Bohannan, G. Z. Brown, and J. L. Green, “Architectural design influences the diversity and structure of the built environment microbiome,” *ISME J*, vol. 6, no. 8, pp. 1469–1479, 2012.

[36] P. Kaarakainen, H. Rintala, A. Vepsäläinen, A. Hyvärinen, A. Nevalainen, and T. Meklin, “Microbial content of house dust samples determined with qPCR,” *Sci. Total Environ.*, vol. 407, no. 16, pp. 4673–4680, 2009.

[37] H. Rintala, M. Pitkäranta, and M. Täubell, “Microbial Communities Associated with House Dust,” in *Advances in Applied Microbiology*, vol. 78, A. I. Laskin, S. Sariaslani, and G. M. Gadd, Eds. 2012, pp. 75–120.

[38] W.J. Sheehan, and W. Phipatanakul. “Indoor allergen exposure and asthma outcomes” *Current opinion in pediatrics* vol. 28 no. 6, pp. 772-777, 2016.

[39] A. Vlasenko, S. Sjögren, E. Weingartner, H. W. Gäggeler, and M. Ammann, "Generation of Submicron Arizona Test Dust Aerosol: Chemical and Hygroscopic Properties," *Aerosol Sci. Technol.*, vol. 39, no. 5, pp. 452–460, May 2005.
[40] U.S Environmental Protection Agency, "A Brief Guide to Mold, Moisture, and Your Home," *Office of Air and Radiation Indoor Environments Division*, September 2012.